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LUNAR-CYCLE MEASUREMENT OF ESTUARINE FLOWS

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HYDRAULICS DIVISION

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LUNAR-CYCLE MEASUREMENT OF ESTUARINE FLOWS

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SYNOPSIS

This paper presents the novel and original "moving boat method" of making complete current-meter measurements of oscillating tidal flows, and also presents unique methods of computation so as to obtain instantaneous values of measured fresh-water outflows, and values of saline interchange. The application of these new methods is described in connection with a continuous series of current-meter and salimeter measurements, spanning a 2-week lunar cycle, made during September, 1954. The measurements of the tidal flows flooding and ebbing the 600 miles of interlacing channels of the confined delta were made at the confluence of the Sacramento River and the San Joaquin River in Central California. The new computation methods result in reliably accurate evaluations of fresh-water outflow. Elaborated details of the processes of the measurement and of the computations are outside of the scope of this paper, but the salient features of both are explained in theory as well as in practice. Final studies and analyses of the results of the measurements have not yet been completed.

INTRODUCTION

The problem of measuring the estuarial tidal flows in the confined outlet of the Sacramento-San Joaquin Delta has been confronting hydraulic engineers and potamologists in the California State Engineers Office for more than thirty years. In general, successive maximum ebb- and flood-flows of approximately 400,000 second-feet occur at the outlet during the summer irrigation season.

No method of standard hydrographic practice of stream-flow measurement lends itself to the many natural obstacles encountered in the wide and deep open-water reaches conveying such magnitudes of flow under such rapidly changing conditions. However, after a series of tests and trial runs of newly devised methods, a full-scale measurement operation was made during September, 1954.

The new methods employed in making the hydrographic observations are no more than unique combinations of standard current-meter practices with the use of new and additional auxiliary equipment. The novel method employed in obtaining current-meter velocities of flow is proposed to be named the "moving boat method" and is herein so designated.

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Sacramento-San Joaquin Delta

For orientation purposes reference is made to Figure 1 which shows the so-called Delta at the confluence of the Sacramento River and the San Joaquin River in the Central Valley of California. These two streams, with their tributaries, comprise the largest portions of the Central Valley of California and drain a watershed of approximately 42,000 square miles, ranging in elevation from 18 feet below mean sea-level in the Delta, to summits above 14,000 feet along the crest of the Sierra Nevada. The island and rim-land areas of the Delta lying below elevation plus 5 feet are comprised of more than 400,000 acres of highly developed irrigated land. The Delta lies immediately south of Sacramento, the capital of California, and about 60 miles inland from San Francisco on the Pacific Coast.

The 600 miles of river and slough channels interlacing the more than 50 islands converge at an outlet point on the west side of the Delta near Pittsburg. Here the converged flow, practically all in one channel, debauches into the head of Suisun Bay, thence through Carquinez Straits into San Pablo Bay, thence into San Francisco Bay and finally through the Golden Gate into the Pacific Ocean. The area of water surface of tidal-affected Delta channels above the outlet at Pittsburg amounts to approximately 40,000 acres.

Salinity Control for the Delta Area

The high quality of the Delta channel waters is maintained by the continued outflow of fresh water from the Delta into Suisun Bay. This outflow counteracts the intrusion of saline sea-water caused by the natural process of tidal diffusion. Prior to the advent of white-men the unregulated natural inflows to the Delta maintained the original fresh-water marsh. Extensive upstream irrigated agricultural development in the Central Valley, with its consequent depletion of summer flows, resulting in a diminution of fresh-water outflow, caused serious degradation of water quality in the Delta channels by the unopposed intrusion of sea-water. During the dry years of 1924, 1931, 1934 and 1939 sea-water salinity reached so far into the Delta as to cause a cessation of summer or fall irrigation on more than 200,000 acres of Delta lands.

Delta Channels Act as Conveyance Link

Releases of water from storage in the now completed Shasta Reservoir at the north end of the Sacramento Valley that are destined for irrigation use in the San Joaquin Valley 500 river miles to the south, are first conveyed down the natural channel of the Sacramento River 260 miles to the Delta, thence southward 70 water miles across the Delta through the Delta channels to a point in the southwest corner of the Delta near Tracy where they are re-diverted and raised 250 feet into the Delta-Mendota Canal to flow southward 120 miles to Mendota. The link in this transfer is the network of tidal channels in the Delta. The key to the success of this transfer is the strict control of sea-water intrusion. Otherwise sea-water would be irretrievably swept into the 4600 second-foot pumping plant near Tracy to ruin crops and soils of more than 200,000 acres in the San Joaquin Valley relying on the pumps for irrigation supplies.

In the very near future will come the State authorized Feather River Project which calls for a transfer of an additional 6000 second-feet through the Delta Cross-Channel, its redirection also near Tracy and its conveyance another 600 to 700 miles to the Los Angeles and San Diego areas of Southern California. Economic feasibility of the Feather River Project demands the use of the Delta Cross-Channel link in conjunction with its use by the Central Valley Project.

The hydraulic and potamological characteristics of these Delta channel network flows working in conjunction with Delta outflows for salinity control, all within the tidal ebb and flood ranges of about 4 feet, are matters not determinable from known observed experiences elsewhere. These characteristics, the quantities of waters involved, and the water-quality aspects can only become reliable as an aid in efficient project operation when the actual outflow of fresh water from the Delta is accurately measured, and the hydraulic equation ($\text{inflow} = \text{outflow} + \text{change in storage}$) can be balanced.

Purposes of Delta Outflow Measurements

The Central Valley Project was planned, designed, and constructed to take advantage of the Delta cross-channels as the vital link in its operation. The conveyance capacity of this cross-channel, the Delta consumptive uses, the accretions to Delta channels from perimeter groundwater tables higher than sea-level, and the requirements for salinity-control water were all unknown quantities and the project had to be, therefore, formulated upon estimates of these aspects. The Shasta Dam unit of the project was put in operation in 1944. By 1954 the gradually developing project demands in the San Joaquin Valley reached a re-diversion rate in excess of 3000 second-feet by the Tracy Pumping Plant into the Delta-Mendota Canal. Consequently, the facts with relation to hydraulic features of the Delta Cross-Channel unit of the project, and measurements under actual operating conditions are now in order.

With respect to the final planning of the newly authorized Feather River Project there must be a reliable determination of the hydraulic characteristics of the Delta cross-channels in order to account for the probable conveyance losses of water that will occur in passing the additional 6000 second-feet across the Delta at sea-level elevations; and its corollary, the design of economic channel improvements to minimize outflow losses.

The current proposal that some type of barrier be constructed somewhere below the Delta and above San Francisco Bay has imposed the question as to the amount of the fresh-water that now flows, or that will flow in the future, out of the Delta for salinity control that can be salvaged for exportation for beneficial use elsewhere.

Inherent in the operation of the Delta Cross Channel as a link in the present Central Valley Project and in presently contemplated projects is the problem of controlling the accumulation of salts in Delta Channels from drainage water from the irrigated lands within the islands of the Delta itself. The maintenance of a salt balance in the island soils and peats is essential to their continued production. A measure of the accumulated salts and the quantities of expurging water required to maintain salt balance are necessary elements in the design of any effected project.

Also inherent in the final analysis of project operation is the complicated question of water rights. In California continued water utilization for beneficial purposes vests and maintains water rights in the lands and communities served.

Usually these uses are readily measurable. However, in the Delta the use is recognized but the amount of the right has been indeterminable. Before the water supply to any project, using the Delta as part of its conveyance system, can be firmly established there must be a practical determination of the water rights for the more than 400,000 acres of the Delta, both quantitatively as well as qualitatively.

Tidal Characteristics

Along the California coast there are two tides a day. The effects of the ocean tides extend far inland through the bays, through all the channels of the Delta, and reach above the City of Sacramento in the Sacramento River to a point 114 miles by water inland from the Golden Gate. During the summer irrigation season the tide range at Sacramento (102 miles from Golden Gate) averages 2.5 feet and at Pittsburg at the outlet of the Delta (48 miles from Golden Gate) it averages 4.5 feet.

A lunar-cycle in this paper refers to a period of approximately 12 to 14 days during which time the Pacific Ocean tides at Golden Gate pass through a more or less harmonic cycle of daily changing patterns. This 2-week cycle is apparent in Figure 3. It is recognized that a true monthly lunar-cycle approximates 28 days. However, the actual expression of the lunar and solar forces upon the tide is the tide-pattern cycle itself which, for practical purposes, is one-half of the monthly lunar-cycle. For simplicity, the one-half cycle is referred to as a lunar-cycle.

It has been the practice in California for 30 years to make 25-hour tidal-cycle current-meter measurements of flows in streams where tidal effects are present. These effects are generally recognized on recorder charts by the twice-daily cycle of gage height changes at any particular station. The flow-rating of such stations must, perforce, be a relation of daily mean gage-height, daily mean tidal slope and daily mean second-feet. In recent years simple formulae have been derived which involve these factors. Nevertheless, substantial departures from the rule occur frequently.

It was discovered that these deviations bear some relation to the shape of the daily tidal pattern. The daily tidal patterns are illustrated in Figure 3. This pattern changes constantly in a rhythmic succession with a cycle period of approximately one-half of a lunar month. The pattern can be seriously distorted in a random fashion by the dynamic forces of changing wind and barometric pressures locally as well as at sea in the Pacific Ocean. The tidal activities in the San Francisco Bay and the Delta are not true tide waves but are, in fact, waves of translation produced from the true lunar tide waves in the Pacific Ocean off the Golden Gate. The rate of translation of each of the two high- and two low-tides each lunar day is not constant. It varies with tide pattern, with channel depths and with local wind movement over the larger bays and extended channel reaches.

The average length of time at each phase of the tide is about six hours. A tide phase is considered, herein, to be the interval between adjacent maximum and minimum gage-heights, to wit, between high-high to low-low, low-low to low-high, low-high to high-low and high-low to high-high, et seq. In fact, however, the time intervals vary widely, as the daily patterns change, with a range of over 8 hours to less than 3 hours. These time variations are illustrated in Figure 3.

With all this interplay of changing lunar (and solar) forces, of local influences, and of random dynamic forces upon the pattern of the tide at the outlet of the Delta it is obvious that a one-day tidal-cycle current-meter measurement of outflow would be of little value by itself. However, a series of tidal-cycle measurements made continuously to embrace an entire 2-week lunar cycle would go a long way toward balancing-out these erratic influences and interacting forces.

Moving Boat Method of Current-Meter Measurement

The standard current-meter used for measuring velocities of stream flow, as it is used in the United States, is recognized as acceptable in stream gaging. It is estimated that at least 80 percent of California's 70,800,000 acre-feet mean annual run-off is gaged by the standard current-meter. However, the reversing tidal velocities at the outlet of the Delta renders the results of the use of a current-meter in standard procedures highly questionable.

Use and Limitations of Standard Current-Meter

The skill required to operate the meter to obtain uniform accuracy and the inherent accuracies of the meter itself are too often taken for granted by the inexperienced engineer. The truth is that the meter produces unreliable results in inexperienced hands and its inherent inaccuracies may lead to serious errors in basic water supply and utilization data upon which a project may be founded.

One of the outstanding deficiencies of the standard current-meter is its inaccuracy in stream velocities of less than one-half foot per second. It is this limitation that has been its undoing in all previous attempts to measure the fresh-water outflow from the Delta. When it is considered that there always exist many points in the channel cross-section where the velocity of the tide during each 6-hour phase at the outlet of the Delta is less than one-half foot per second and that a slack-water reversal occurs every six hours, it is apparent that the standard current-meter, suspended in fixed position as heretofore employed, is unreliable.

During the times approaching and following slack-water the direction of water movement is indeterminable. At any instant, opposite velocities have been observed at different meter sections across the stream. The direction of the velocity obtained by a current-meter with fixed point suspension has in the past been purely a "guess" near slack-water reversal times, since the meter is out of sight and its suspension cable hangs virtually vertically.

It was therefore clearly obvious that the old standard methods of making current-meter measurements must be improved or else some entirely new type of instrumentation must be devised. The hydrographic section of the State Engineer's Office has studied this problem vigorously for the past five years. A great deal of study and planning was done on ideas to measure oscillating stream velocities by means other than using the standard current-meter. Experienced hydraulic engineers and hydrographers with the State and with the U. S. Geological Survey have discussed the problem at length.

Principle of Moving Boat Method

Finally there emerged an entirely new method of employing a standard current-meter to measure the low velocities as well as the zero and near zero velocities present in tidal channels during the slack-water times of each tidal phase. This new "moving boat method" injects into the apparent velocity of the meter and added constant velocity of known rate. Field tests were made in still water and in flowing streams, and these tests indicated that high accuracies are readily obtainable.

The tests pointed out the special equipment and the improvements in techniques that would be needed for a full scale lunar-cycle measurement.

The new method is a simple one. Instead of tying the measuring boat, from which the meter is suspended, to an anchored buoy or to a tag-line at

successive meter sections across the stream, the boat is kept moving at a constant speed against the current. The velocity of the boat with respect to the shore is determined accurately from the shore. The velocity of the water with respect to the boat is measured in the usual manner by current-meters. By subtracting the speed of the boat with respect to the shore, from the speed of the water with respect to the boat, the speed of the water with respect to the shore is obtained. Thus, it can be said, the current-meter is used to measure a zero stream velocity, accurately. This moving boat method keeps the meter speed in its optimum velocity range of two to six feet per second. This method is illustrated in Figure 2.

Measuring Procedure Using Moving Boat Method

Shore Equipment

At the selected site two parallel range-lines, 200 feet apart, are established across the channel perpendicular to the thread of the stream. An engineering transit is set at one end of each line. A fore-sight, equipped with lights for night observation, is set on the opposite shore at the other end of each range-line. An electric stop-watch is provided with push-button switch extension wires lined out to each transit. The speed of the moving boat crossing the two range-lines is thereby measured with cross-hair accuracy

Marker Buoys

Two rows of anchored marker buoys are set across the channel, one about 100 feet upstream from the upstream range-line and the other about 100 feet downstream from the downstream line. The spacing of these marker buoys is predetermined to indicate the position of the successive current-meter sections in accordance with standard practice in that regard. With only one buoy on each section the upstream and downstream buoys alternate. Thus the boat-pilot needs only to line-up with one buoy for each section to set his compass course and is thereby not influenced in setting his course by any relative mis-alignment if two buoys were on one course. Mis-alignment may occur during slack-water when the buoys swing on their long anchor ropes to take a new position.

The marker buoys are made by inflating an automobile tire inner-tube between two wooden crosses fastened in their centers. The tube and wooden crosses are sprayed either bright orange or white and are numbered in bold-black figures for meter section identification. Each buoy is equipped with a red light consisting of a red flashlight bulb simply snapped onto the spring contact points of a standard four cell lantern battery. The battery with its light on top is placed inside of an upside-down clear glass screw cap pickle jar. The metal screw cap is fastened on top of the wooden cross. The batteries are replaced daily. Anchor ropes are cut at least two times the depth of the specific position. Precast 200-pound concrete blocks with an insert eye-bolt were used as buoy anchors.

Path of Measuring Boat

The path of the measuring boat during one full channel crossing measurement is a zig-zag one. Reference is made to Figure 2. Assuming an ebb-tide, for illustration, the boat would be pointed upstream when making a meter-section run. The pilot pulls the boat around below a downstream buoy and sets his course parallel to the thread of the stream by compass. The engine throttle is set at minimum speed and the measuring-run is started. The boat crossings of both range-lines are observed on shore through the transits and the time of crossing is indicated by the electric stop-watch.

Upon completion of the run the boat is veered through an "S" turn and would then be in position for the next run in line with the adjacent buoy. Generally, the direction of the boat is set against the direction of the flow.

Thus, where there are fourteen meter sections across the channel and only velocity observations are made, one full channel crossing requires approximately one-half hour. When salimeter observations are made, as in this case, the crossing time is doubled. Immediately upon completing a channel crossing the boat is returned to the starting shore and the whole procedure is repeated. In this manner, each meter-section across the channel is measured at approximately one-hour intervals throughout night and day for the entire period of the lunar-cycle.

Boat Equipment and Its Use

A boat with ample deck working space, with a large screw and reserve power to have good steerage at low speed, with fuel storage for many days of continuous operation, and with cabin facilities to house sensitive salimeter recording instruments, is requisite to this operation.

Two current-meters are continuously used for these measurements. One is set at 0.2 of the total depth at each meter-section and the other at 0.8 of that depth. Each meter was cable-suspended separately by means of special wooden booms affixed over each quarter of the bow of the boat. At the beginning of each measuring-run of the boat the current-meter men lower their current meters to depth settings based upon the predetermined mean depth at the section and adjusted by the momentary gage-height of the stream. Each meter man times his meter while the boat is running the course. Thus, simultaneous with the measurement of the speed of the boat with respect to the shore, the speed of the water with respect to the boat is measured by use of the standard "0.2 and 0.8 depth method."

Handy-Talkie two-way radio sets were put on shore and on board the boat, and thereby a constant cross-check of data and of ship and shore activities are accomplished. The radio system is essential in relaying current gage height information for meter settings.

The measuring boat is also equipped with salimeter apparatus. Suspended by cable over a boom near the stern of the boat is a conductivity double-cell unit. During or at the end of each measuring-run the unit is lowered to the bottom of the section at equal depth increments. One of the conductivity cells is sealed with the electrodes in a standardized solution, the other is open to channel water. The cells are the opposing arms of an automatic electronic recording wheatstone bridge. Thus a complete salinity traverse both in depth and in width, is recorded for each hourly channel crossing. Operation of this salimeter apparatus requires a 120 volt a.c. generator on board ship.

Prevailing water temperatures are also recorded electrically on board the boat by means of a thermo-sensitive cell suspended overboard and its associated stilus recorder. The temperature traverses follow with the salinity traverses.

1954 Delta Outflow Measurement

The 1954 Delta outflow measurement was planned and accomplished in the light of experiences gained from a 60-hour tidal-cycle measurement made in the two main outflow river channels of the Delta in September 1953. Analyses of the results of the earlier measurement revealed, amongst other difficulties, that any period of continuous observation shorter than a lunar-cycle (14 days) does not embrace a cyclic period of equilibrium of the lunar forces. It was

also revealed that the immeasurable effects of the heretofore mentioned random forces of short duration so outweigh the quantitative results as to make them unreliable.

The principle of observing cumulated repetitions, as a means to obtain a high degree of accuracy, is the basis for the accuracy in these current-meter and salimeter measurements. It was found that a 60-hour period permitted only two distinct 25-hour tidal cycles containing only nine tide phases. The tide pattern constantly changed and an equilibrium was not reached. In consequence, the 1954 measurement, extending for 17 days and including 66 tide phases, was designed to embrace a full lunar-cycle. In this manner, time permitted a cyclic repetition at the end of the period of the same tide pattern experienced at the beginning of the period. Thus, a period of equilibrium was established and by dividing the integrated repetitions of ebb- and flood-flows by the number of unit time intervals an accurate value of the mean rate of fresh-water outflow is obtained.

Site Selection

The selection of the site for making the measurement was based primarily upon the desire to measure all of the flow in one channel. Consequently a section across the Sacramento River at the Chipps Island reach was selected as shown in Figure 1. This site is below the confluence of the San Joaquin River with the Sacramento River at Collinsville and is above Suisun Bay. Two small tidal sloughs by-pass this site, and full and continuous measurements of their flows were also made as are later described.

This site lies across a river reach about 2-1/2 miles long with only a slight curvature but with practically parallel shores. The reach approximates 3700 feet wide with a slightly undulated bottom having a maximum depth of approximately 50 feet at mean tide. Automobile access to one shore and nearby docking facilities were available.

Preparations for the Measurement

Prior to the measurement a survey of the channel bottom across a 1000 foot wide strip at the site was made by echo-sounding apparatus, and a contour map was prepared. A paper location of the two range-lines were checked by actual plumb-weight sounding and the lines were then established on the site. Range-line poles and lights were set. Range-line cross-sections were drawn and fourteen current-meter sections were located so that cross-section areas would be nearly equal. Since the new U.S.G.S. standard "mid-section method" of computing current-meter notes would be used, a tabulation of areas for each meter section for each 0.1-foot change in gage-height was prepared. Another tabulation showing the 0.2 and 0.8 depth settings of the current-meters for each 0.1-foot change in gage-height for each meter section was prepared for ready use.

Marker buoys were constructed in the manner heretofor described. Although a "notice to mariners" describing this operation was sent to all river boat pilots in the area, some buoys were lost because they were spaced relatively closely and some of the long and wide barge tows passing through the measuring reach carried a few buoys away. At the outset extra buoys were constructed and were used for replacement as needed.

The buoys were put into position the day before the start of the measurement and were located by triangulation.

A local staff-gage was established and an automatic water-stage recorder

was installed over a dampened float stilling-well nearby.

Wind shelters were constructed on shore for the notekeeper and for each transit on the ends of the range-lines.

The preparation of measuring sites on the two small side-channels consisted of the presounding of the sections, the stringing-out the standard tag-lines across the streams, the establishment of local staff-gages, and the installation of local recorders.

A small cabined service boat was used to take care of crew shift changes, to rescue and replace damaged buoys, and to tend the night lights on the buoys and on the opposite shore.

The more than thirty recording tide gages located in the Delta area upstream from the measuring site were serviced and checked at the beginning of the measuring period, at the end of the period were again checked and their charts removed for use in later office computations.

Manpower Requirements

The measurement continued for seventeen days, around the clock, and with virtually no breaks in schedule. Three 8-hour shifts of hydrographers were assigned to the operation. The main outflow channel measurement required a total of thirteen personnel consisting of: two transitmen and one combination party-chief, notekeeper and radioman on shore; two current-meter men, one combination notekeeper, radio-man and look-out, two salimeter deck men, one salimeter instrument man, and one pilot on board the measuring boat; one service boat pilot; and one supervisor and one assistant supervisor to act in emergency replacement and to tend buoys and lights. The two side channels required two hydrographers on each channel for each shift. A grand total of approximately 50 hydrographers were assigned to this 17-day measurement.

Computation Methods

The usual method of computing flows from current-meter observations result in obvious errors when applied to tidal channels. The usual method, in general, is to treat all of the current-meter section observations as if they were made practically instantaneously, and a summation of the AV (area x velocity) values of each section is the measured flow. In a normal flowing stream such treatment is standard practice. However, in this case where there exists as much as a 5-foot change in stage in six hours, a change in velocity from a plus 3.0 feet per second to a minus 3.0 feet per second in six hours, and a probable unequal time interval between current-meter velocity observations, the usual method must be replaced by a new method which will maintain the integrity of a true instantaneous measurement of flow. There was, therefore, evolved a new computation process chosen to be called the "parallel-section method." This method was used in the main channel computations.

Parallel-Section Method of Computing Current-Meter Notes

This novel method is primarily useful in computing tidal-cycle current-meter measurements. It is based upon the simple concept that the flow passing through each of the current-meter sections is a separated parallel stream in its own right. The computation process therefore embraces the separate computations of fourteen separate streams (as in the case of this

measurement) for the entire 17-day series of single-section mean vertical velocity observations.

The next step in the process is the construction of a 17-day parallel-section hydrograph of flows in second-feet for each of the fourteen sections using the single-section AV values as the plotted points at the actual times of observation. Visual inspection of these hydrographs offers an opportunity to discard or correct any single point which might be obviously a wild one in comparison with the pattern of the other thirteen graphs.

The next step is to construct an instantaneous measured-flow hydrograph as illustrated in Figure 4. This graph is a composite of the fourteen separate hydrographs. The points are plotted at regular half-hour intervals with ordinate values equal to the algebraic summation of the interpolated values of flow for the particular time from each of the parallel section hydrographs.

This instantaneous measured-flow hydrograph now becomes the basic quantitative measure of the tidal ebb and flood movement of water passing the measuring site in the main channel. It is obvious, then, that the rate of mean flow of fresh-water outflow between any two times on the hydrograph is equal to the algebraic summation of the intervening ebb- and flood-flows.

These measured flows must be modified by two other measured variables: one, the quantities of ebb- and flood-flows occurring in the two measured side-channels; and two, the change in tidal-volume storage in the more than 600 miles of tidal channels in the Delta above the measuring site. The two modifications are dealt with in the following paragraphs.

Side-Channel Flow Computations

Each of the two side-channels were measured approximately hourly concurrently with the measurements of the main channel. Because of their relatively small widths and depths the usual methods of current-meter tidal-cycle measurement were employed. This method involved the use of a small boat fastened to a tag-line across the channel. Flow computations were made by the usual method of summation of each current-meter section AV value without resort to the parallel-section method.

A measured-flow hydrograph was prepared for each of the side-channels by plotting the total cross-sectional flow against the mean time of measurement. These hydrographs cover the seventeen days of measurement which embraces the actual time of the lunar-cycle, the same as does the seventeen day instantaneous hydrograph prepared for the main channel. Maximum flow in either channel was about 6000 second-feet.

Tidal-Volume Storage Change Computations

These computations, at best, are laborious and involve consideration of continuous records from thirty gage-height recorders covering the 600 miles of Delta tidal-channels. The total Delta channel water-surface area of 40,000 acres was broken into thirty sub-areas. The limits of each sub-area was determined by estimating the length of the specific channels which would probably show the same gage height changes as would be recorded by the nearby tide-gage.

Since only changes in tidal storage are essential in these computations the absolute elevation of the channel water-surfaces plays no part, and the standing question as to the accuracy of tide-gage datum for gages located on peat island levees does not enter. It is presumed, however, that each tide-gage recorder offers an accurate measure of change of water-surface elevation.

The actual change in Delta channel volume is therefore the algebraic summation of the products of sub-area acreage by the water-surface elevation change at the corresponding recorder.

A summation hydrograph of Delta volumes is then prepared. A plotting of the first two and last two days of this hydrograph is illustrated in Figure 5. This hydrograph exhibits the same positive and negative lobes with the same oscillation period as are expressed both in the instantaneous measured-flow hydrograph and in the tidal gage-height graph, illustrated in Figures 4 and 3, respectively.

Measured Surface Inflow to and Diversions From the Delta

Simultaneously with the 17-day measurement of Delta outflow and the changes in Delta tidal-volume storage observations and measurements were made (1) of the flows in the surface streams entering the Delta at gaging stations located above tidal influence, and (2) of the discharge of pumping plants around the perimeter of the Delta which is delivered to lands outside of the lowland Delta area.

Continuous stream-flow records are maintained on the six major streams tributary to the Delta. There are many ephemeral streams entering the Delta but their flows during September are virtually zero. Thus, an accurate record of daily mean surface inflow of fresh water to the Delta channels is available.

Diversions from the perimeter channels of the Delta are made by more than 100 pumping plants, including the Tracy Pump Plant and the Contra Costa Canal Pumping Plant which are the major pumping units of the Central Valley Project. Capacities of pumping plants range from one second-foot to 4600 second-feet. During the 17-day course of the outflow measurement varying operation of these plants was experienced. However, daily operation records of all of the plants provided an accurate daily mean rate of diversion from the Delta during the period of the measurement.

Net Surface Inflow to Delta

The daily net surface inflow to the Delta channels is therefore the difference between the daily mean measured surface stream inflow minus the daily mean diversions. This item is used in the final computation to solve the complete hydrologic equation for the Delta.

Lunar-Cycle Mean Flow Computations

It has been heretofore pointed out that the daily changing tide pattern makes it impracticable (if not impossible) to obtain an accurate value of tidal mean flow from a measurement lasting for less than a lunar-cycle. The next problem in this computation process is to determine the times of beginning and ending of the lunar-cycle when some one of the variable items is in equilibrium. There are three items which are cyclic and which, therefore, pass through equilibrium points, namely, tide gage-heights, slack-water between ebb- and flood-flows, and Delta tidal-volume.

Consideration is first given to "times of equal tide gage heights." From Figure 3 it can be seen that there is a substantial daily change in the heights of any one of the four daily peaks (that is, high-high, low-low, low-high or high-low), but that after about thirteen days the corresponding heights are more or less repeated. Noting the times of equal gage-heights, and referring to Figure 4, the corresponding values of measured out-flow are not equal. Similarly by referring to Figure 5, the corresponding values of tidal-volume are not equal. A solution of the equation on this basis is, therefore, least desirable.

Consider next the times of equal measured outflow. It is apparent from Figure 4 that any two slack-water times represent equilibrium with respect to tidal flow. However, for corresponding slack-water times, it is noted from Figure 5, that tidal volumes are not equal, and similarly from Figure 3 tide heights are not equal. A solution on this basis is also not desirable.

Final consideration is given to "times of equal tidal-volume" as the determining factor of equilibrium in arriving at the instants of beginning and ending of the lunar-cycle. By choosing times of equal tidal volume the item of tidal-volume change goes out of the hydrologic equation and the equation is reduced to the terms of accurately measured flow and to only one unknown, the net use of water in the Delta area.

Times of Equal Tidal-Volume Method

The final computation of the Delta hydrologic equation is based upon the period between times of equal tidal volume above the outflow measuring site. The beginning and end of this period are selected from the hydrograph of Delta volumes, Figure 5, so that the times of equal tidal volume closely coincide with the same phase of a similar daily tide pattern repeating after a thirteen-day interval.

This computation process is illustrated by referring to points a-a shown on Figure 5 and Figure 4. On Figure 5 the times of equal tidal volume are 311 hours and 45 minutes apart, beginning at 0100 on September 13 and ending at 0045 on September 26. These two times are transferred to Figure 4. The desired value of mean measured outflow is therefore the algebraic summation of measured ebb- and flood-flows between the times of equal tidal volume indicated by a-a on Figure 4. This process can be repeated for any number of time intervals between times of equal tidal volume.

The application of this method of computing tidal flows between times of equal tidal volume is believed to be novel. It is also believed that any computations of estuarial flows involving an extensive network of tidal channels, flanked by undefined areas of flooded berms, must use this method to obtain reliable accuracy. In the case of the Sacramento-San Joaquin Delta where the channels extend fifty or more miles inland a low-tide occurs at the outlet of the Delta while the previous high-tide still exists in the upstream reaches, and vice versa. In consequence of this phenomena, and because of the inherent errors in tidal-volume computations due to possible errors in channel water-surface acreages, it is highly desirable to eliminate the item of change in tidal-volume from the final equation. The use of the method of times of equal tidal-volume accomplishes this elimination and thereby increases the accuracy of the final solution.

Solution of Delta Hydrologic Equation

It was pointed out in the introduction to this paper that the cross-channels of the Sacramento-San Joaquin Delta act as the connecting link in the conveyance southward of the abundant waters of the north to the water-deficient areas in the south. Basic in the satisfactory operation of this link is the control of sea-water intrusion into the cross-channels. This control is obtained by the provision of a fresh-water outflow in quantities sufficient to counteract the natural infusion of saline sea-water. Also inherent in the operation is the provision of a fresh-water supply for irrigation of the nearly 400,000 acres of Delta. By the nature of the hydrology of the Delta this irrigation supply must be expressed not in gross irrigation application but in terms of net use. As heretofore mentioned, the quantity of the fresh water which is

depleted by the consumptive use processes (evapo-transpiration) has not been actually measured and is considered in this paper to be an unknown in the Delta hydrologic equation.

Net Use in Delta

It is recognized that the below sea-level elevation of much of the island area may promote in some localities an accretion to the water supply from groundwater surrounding the Delta where the elevation of the groundwater table is conducive to movement toward the Delta. Prior to the advent of deep-well pumping for irrigation onto lands lying back from the Delta residual groundwater movement under-lying hundreds of square miles of the floor of the Central Valley gravitated into the Delta area as accretions from groundwater. However, groundwater elevation observations at the present time indicate that there are sizeable areas of depressed groundwater levels partially surrounding the Delta where some replenishment from perimeter Delta channels may occur.

Irrigation water for nearly 400,000 acres in the Delta is derived from the waters in the channels surrounding the islands. Diversion is made (1) by means of uncontrolled direct seepage through or under the levees or by pipe siphons over the levees to serve the lands below sea-level, and (2) by means of pumping over the levees and onto sedimentary lands lying at or above sea-level. Approximately one-half of the area lies below mean sea-level. There are no means of measuring the amounts of gross irrigation applications to the Delta islands because of the immeasurable rates of seepage from sea-level channels toward the centers of the islands lying below sea-level.

Net use, as applied to the Delta area, must, perforce, be a computed figure derived as the difference between the measured surface stream inflow and the measured surface stream outflow between times of equal Delta tidal volume. This net use is therefore the actual result (1) of the unmeasured losses by evapo-transpiration and by underflow to back-lying groundwater and (2) of the unmeasured accretions from surrounding higher groundwater tables and from minor unmeasured surface drains tributary to the Delta channels. The net use figure derived from the equation is therefore a factual computation, and as such it is highly important in the operation of the Delta Cross-Channel link of the Central Valley Project and of contemplated projects likewise using the same link.

The Equation

The foregoing exposition of the various terms of the Delta hydrologic equation makes it now possible to set-up the equation. The following itemization formulates the equation in descriptive words. It is obvious, in the final analysis, that this equation is in the simplest form of reservoir equation in which "inflow equals outflow plus or minus change in storage and reservoir losses."

Hydrologic Equation

Mean Measured Flows
September 11, to
September 27, 1954

(Second-feet)

INFLOW

- | | |
|--|-------|
| 1. Surface stream flow of
tributaries to Delta channels | 11790 |
|--|-------|

OUTFLOW

- | | |
|--|------|
| 2. Diversions by pumping plants
from perimeter Delta channels | 2340 |
| 3. Surface stream outflow in
main outlet channel | 7600 |
| 4. Surface stream outflow in
side channels at outlet | 80 |
| 5. Rate of change of Delta
tidal-volume | 0 |
| Total outflow | 9860 |
| 6. Net use in Delta area (computed) | 1930 |

In the preceding itemization the results of the observations and measurements made in September, 1954, have been included for realism. Item (6) is the unknown term solved by the equation. The figure of net use of 1930 second-feet in September, 1954, differs from the long accepted figure of 2870 second-feet as the consumptive use of Delta lands during September of any year because of possible errors in assumed consumptive use values and because no measurement of actual accretions have ever been made.

At the time of preparation of this paper studies and analyses of the results of the September 1954 Delta outflow measurement have not been completed. Effects upon future hydrologic studies and project planning cannot be predicted at this time. Without a doubt, further studies will discover new and important features of tidal hydraulics relating to cross-conveyance of fresh water in tidal estuaries.

Salinity Interchange in Delta Outlet During Lunar-Cycle

It has been previously described that, simultaneously with the measurement of stream velocities by means of the moving boat method, observations and measurements of salinity concentrations in depth were made at each current-meter section across the channel. Calibrated results of the measurements gave a more or less continuous record of the amounts of dissolved salt at the same intervals that velocities were measured.

Therefore, by using the same method of parallel-sections as was used in computing flows, a salinograph was prepared for each parallel-section. From the hourly values of second-feet flow derived from the parallel-section hydrograph (Q) and the corresponding hourly values of concentration from

the salinograph (C) for the corresponding section, a set of hourly CQ values was derived for each section.

As in the case of the preparation of the instantaneous measured-flow hydrograph, all of the CQ values for each hour for each measuring section were combined and an instantaneous salt-movement hydrograph was prepared covering the entire 17-day period of the measurement. The CQ values were computed not only for the main channel but also for the two side-channels.

The CQ values actually used in the final computations are not simply the product of salt concentration and flow but have been converted in the process to be expressed as salt in tons per hour. Thus, the actual interchange of salt between any two times on the instantaneous salt-movement hydrograph is equal to the algebraic summation of the intervening ebb and flood movements of salt.

A finished study and analysis of the salinography of Delta channels and of Delta outflow has not been completed by the time of preparation of this paper. New and important discoveries with respect to salinity conditions in the Delta are to be expected as these studies progress.

Discussion of Results

Prior to the full-scale lunar-cycle flow and salinity measurements made of the outflow of the Sacramento-San Joaquin Delta in September, 1954, the Delta hydrologic equation was insolvable because there were more unknowns than equations. Studied estimations had to be relied upon to indicate the probable fresh-water requirements of the 400,000 acres of Delta lands and to predict the probable hydraulic and salinity characteristics of the Delta channels. Those conjectures were used to formulate plans for the conservation and utilization of the Central Valley's water resources.

The results of the lunar-cycle Delta outflow measurement, though final analyses are far from complete, indicate that some modifications are in order of some of the earlier estimates of Delta factors in the over-all conservation scheme.

Accuracy Characteristics of the Measurement and Its Computation

The seventeen-day measurements of tidal flow and concurrent salinity provided a series of repetitions of observations of 33 ebb-tides and 33 flood-tides. This repetition process, in itself, is a prime factor in assuring reliable accuracy of results. The lunar-cycle period is of such length as to permit of a practical re-establishment to equilibrium of many of the random forces which make short period observations unreliable. The random forces of wind, barometric-change, temperature changes in evapo-transpiration ratio, abnormal tide-patterns and the regular daily change in tide pattern are all minimized, if not entirely balanced-out, during the lunar-cycle.

The use of the moving boat method of stream velocity measurement by a current-meter permits of the highest possible accuracy obtainable from the standard current-meter especially at low velocities.

Tests of the accuracy of the use of the 0.2 and 0.8 depth method of positioning the current-meter indicated that this method is acceptably reliable as used in the reversing tidal-flow velocities. The tests were made independently, but during the course of the 17-day measurement, by measuring velocities in the vertical by the multiple-point method in direct comparison with the 0.2 and 0.8 depth method.

The parallel-section method of computation permitted the development of a true instantaneous hydrograph of rates of tidal flow. The instantaneous flow hydrograph is essential to reversing tidal-flow computations and is also a prime factor in assuring reliable results.

The employment of the "times of equal tidal-volume" method of determining tidal-equilibrium conditions in the computation procedure practically eliminates the large source of error, which would otherwise enter the final computation, stemming from upstream estuarial volume observations.

Recommendations

The novel and original methods of measurement and computation of estuarial tidal-flows, as presented in this paper, are recommended as practicable and useful wherever flows, particularly of larger magnitude, are encountered and where a high degree of accuracy is desired.

The moving boat method of current-meter measurement is recommended for any continuously flowing stream or channel where velocities of less than one-half foot per second are to be measured anywhere in the section. This method actually extends the range of use of the standard current-meter down to a velocity of zero. In fact, as demonstrated in the above described measurement, negative velocities can be measured by observing positive rotation of the meter with no loss in accuracy.

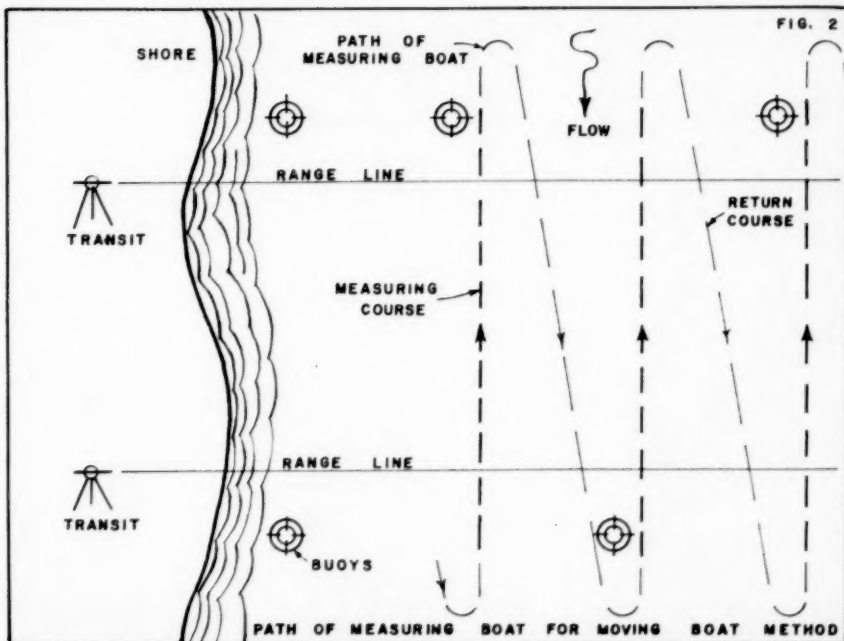
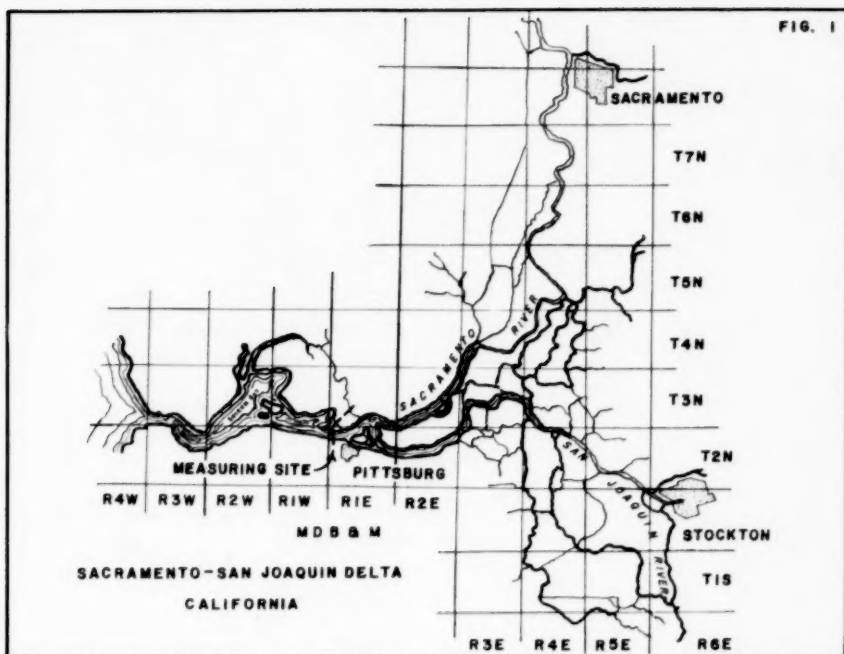
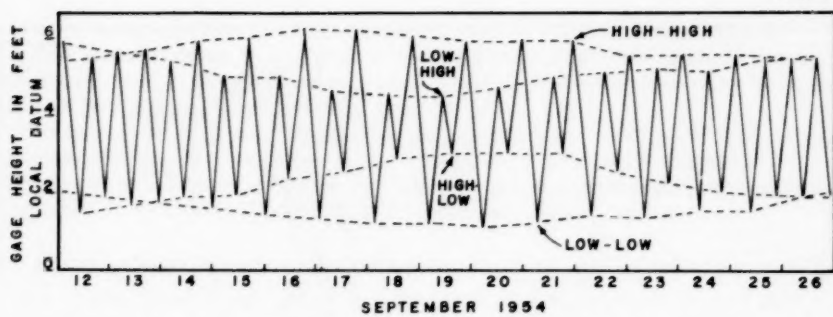


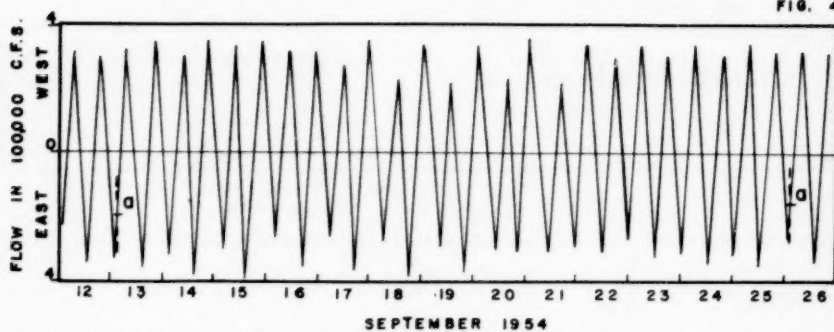
FIG. 3



TIDAL GAGE - HEIGHT GRAPH

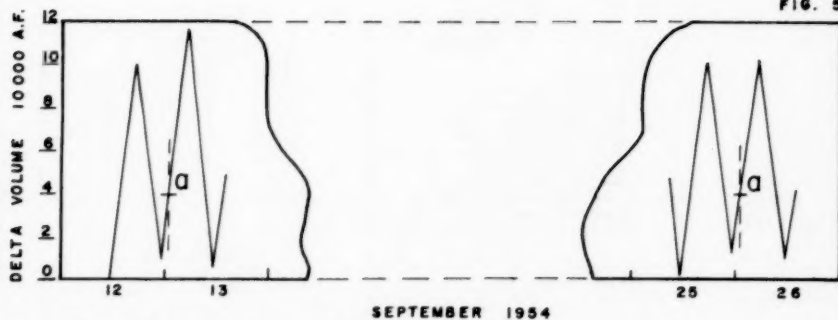
SACRAMENTO RIVER OPPOSITE
CHIPPS ISLAND

FIG. 4



INSTANTANEOUS MEASURED - FLOW HYDROGRAPH

FIG. 5



TIDAL - VOLUME CHANGE HYDROGRAPH